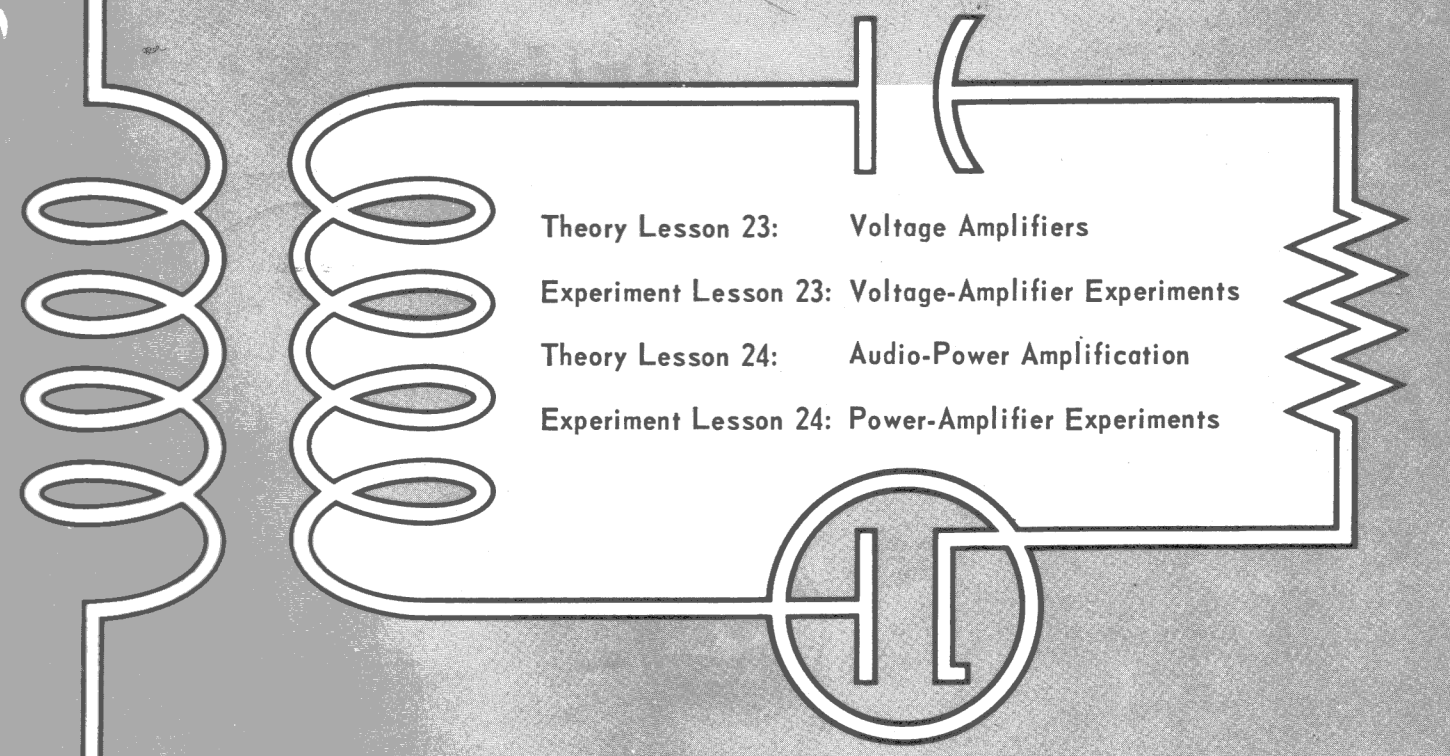


ELECTRONIC FUNDAMENTALS



Theory Lesson 23: Voltage Amplifiers
Experiment Lesson 23: Voltage-Amplifier Experiments
Theory Lesson 24: Audio-Power Amplification
Experiment Lesson 24: Power-Amplifier Experiments

RCA INSTITUTES, INC.

A SERVICE OF RADIO CORPORATION OF AMERICA
New York, N. Y.



ELECTRONIC FUNDAMENTALS

THEORY LESSON 23

VOLTAGE AMPLIFIERS

- 23-1. Amplifier Classes**
- 23-2. Audio-Frequency Voltage Amplifiers**
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Theory Lesson 23

INTRODUCTION

The main use of electron tubes in radio and television receivers is to *amplify* signal voltages. We know that to amplify means to make larger or stronger; to increase in value. As the word applies to radio and television receivers, it means to increase signal voltage or current to a usable level. It is easy to see that amplifiers are needed when one considers that the signal picked up by the receiver antenna is measured in microvolts. As is shown in the block diagram of Fig. 23-1, the modulated r-f signal picked up by the receiver antenna is amplified and then detected, which, as you know, means that the signal is demodulated (freed from its r-f component), leaving only an audio signal. However, the audio signal needs further amplification before it may be used to drive a loudspeaker and be heard.

The amplifiers used in radio and television receivers may be divided into two main groups: *voltage* amplifiers and *power* amplifiers. However, we can say that a voltage amplifier increases the signal voltage without regard to the amount of current flow, and a power amplifier produces large signal current in the load without regard to voltage. Power amplification is the subject of the next lesson. The purpose of this lesson is

mainly to tell you about voltage amplifiers used in audio circuits.

23-1. AMPLIFIER CLASSES

One way of classifying amplifiers is according to the class of tube operation. The class of operation of an electron tube is determined by the selection of the operating point, which in turn depends on the amount of negative d-c bias voltage that is applied to the control grid of the tube. The main classes of operation are: A, B, AB, and C.

Class A Operation. Class A operation exists where the grid bias and the alternating (signal) voltages applied to the control grid are such that plate current flows during all parts of the signal cycle. Figure 23-2 shows the operating point *O* in the center of the linear portion of the plate-current grid-voltage curve. This produces less distortion than would result from having the grid voltage swing into the curved portion near *X* or *Y*. However, it is not necessary that the tube operate only in the linear portion to operate class A. If plate current of a tube flows throughout the entire signal cycle, the tube is operating class A, no matter how much

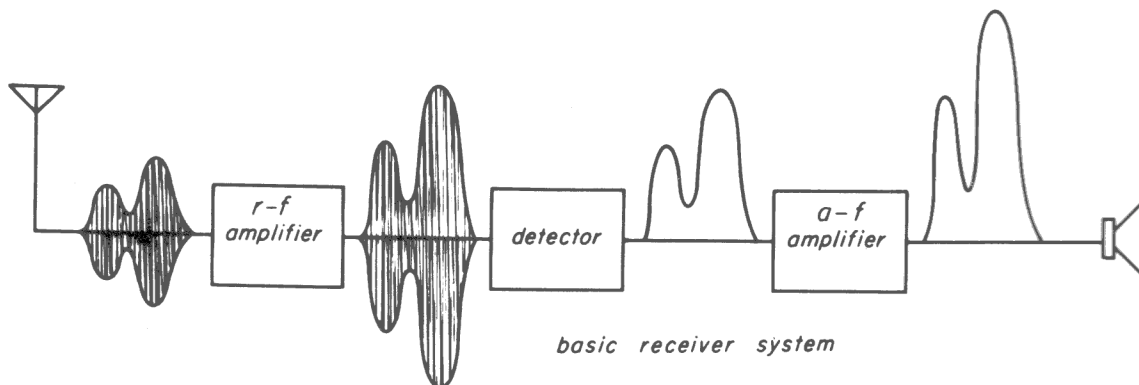
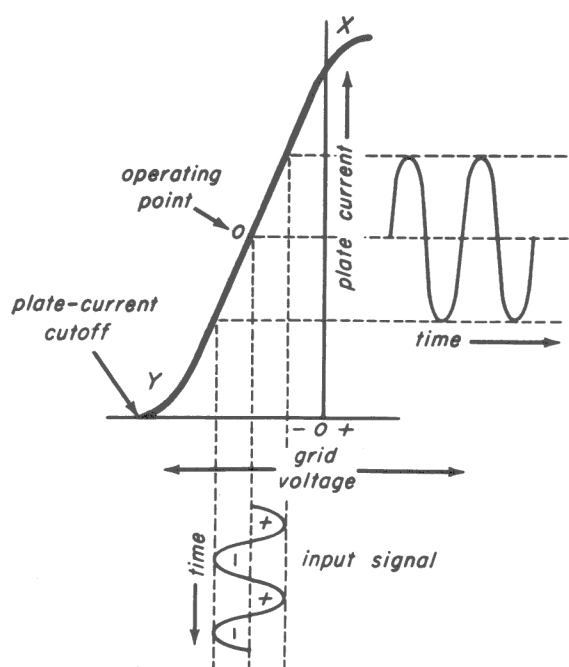


Fig. 23-1

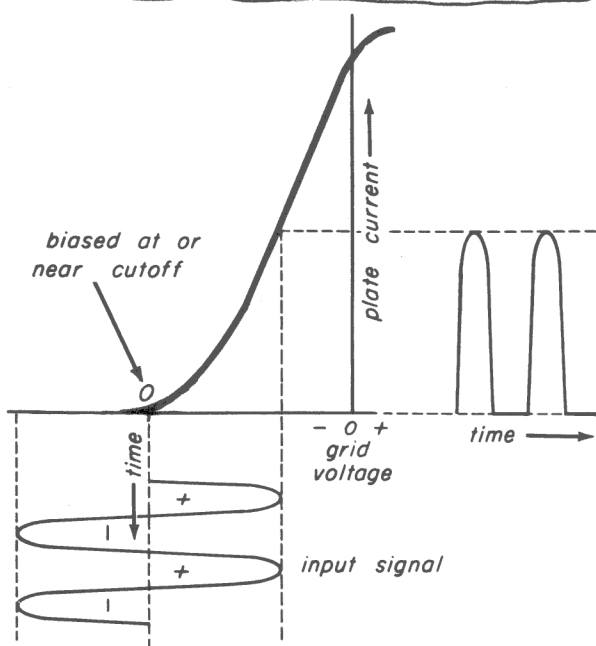


class A operation

Fig. 23-2

distortion may result. Most amplifiers used in radio and television receivers operate class A.

Class B Operation. Class B operation exists when the grid bias approximately equals the cut-off value. In class B operation, plate current flows only when a signal

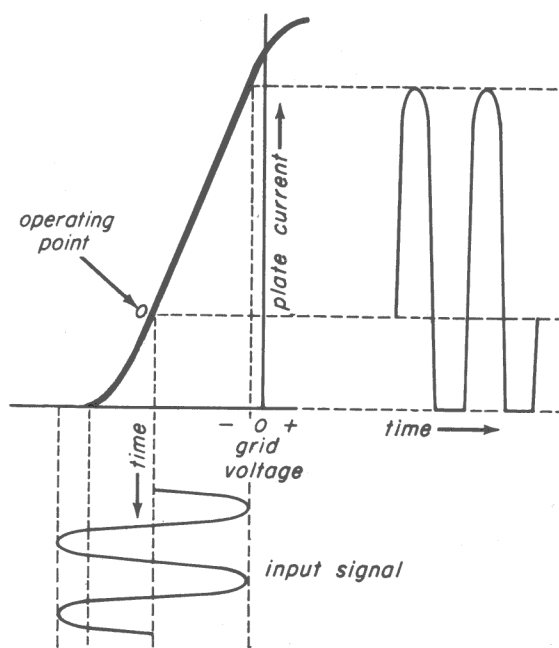


class B operation

Fig. 23-3

is applied to the grid and when the signal is in its positive half cycle. No plate current flows during the signal's negative half cycle. When the tube is biased to cutoff, as in Fig. 23-3, it is operating class B, which causes the tube to operate in the lower curved portion of the plate-current grid-voltage characteristic curve, and causes distortion. For this reason, single-tube class B voltage amplifiers, particularly in audio circuits, are seldom used. Because class B operation permits a greater plate-current swing for the positive alternation, more power is obtained from such operation. When combined in special circuits that reduce the distortion, class B amplifiers give satisfactory results. Such circuits are discussed in the power-amplifier lesson.

Class AB Operation. Class AB operation is between class A and class B. Therefore, in class AB operation, plate current flows during more than half the signal cycle and less than the entire signal cycle. Class AB operation is divided further into two subclasses: class AB₁ and class AB₂. The subscript 1 shows that no grid current flows during a portion of the signal cycle. The subscript 2 indicates that grid current flows during a portion of the signal cycle. A tube operates class AB₁ (Fig. 23-4) when the



class AB₁ operation

Fig. 23-4

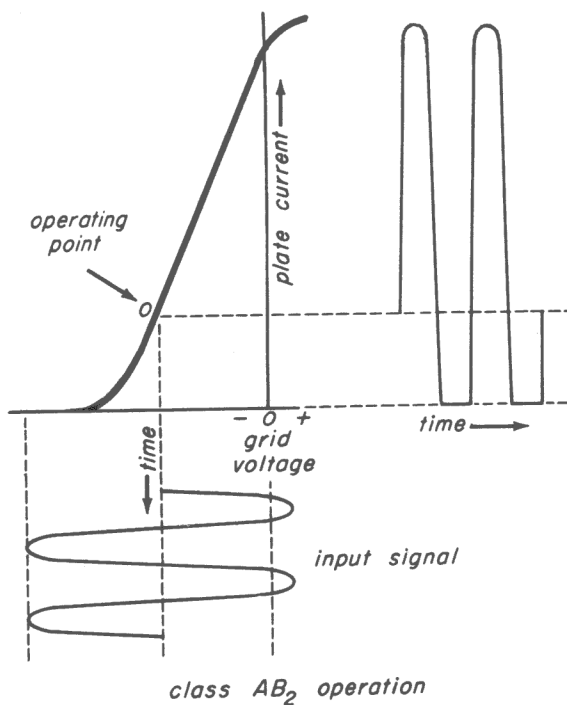


Fig. 23-5

operating point is somewhere between cutoff and the center of the linear portion of the curve, and the positive peak of the signal does not cause the grid voltage to swing positive. A tube operates class AB_2 when the operating point is somewhere between cutoff and the center of the linear portion of the curve, and the positive peak of the signal causes the grid voltage to swing positive (Fig. 23-5). Like Class B operation, class AB operation is limited mostly to power amplifiers.

Class C Operation. A tube operates class C when: (1) its operating point is measurably beyond cutoff; (2) a positive signal alternation causes plate current to flow during less than half the signal cycle. If the signal does not drive the grid voltage positive so that grid current flows, the subscript 1 may be added (C_1). If the grid voltage is forced positive and grid current flows, the subscript 2 may be added (C_2). Figure 23-6 shows a typical curve for Class C operation. Note that the plate current flow for less than 180° of signal input cycle; also, the grid goes slightly positive. Class C operation is generally used in r-f oscillators and r-f amplifiers in transmitters.

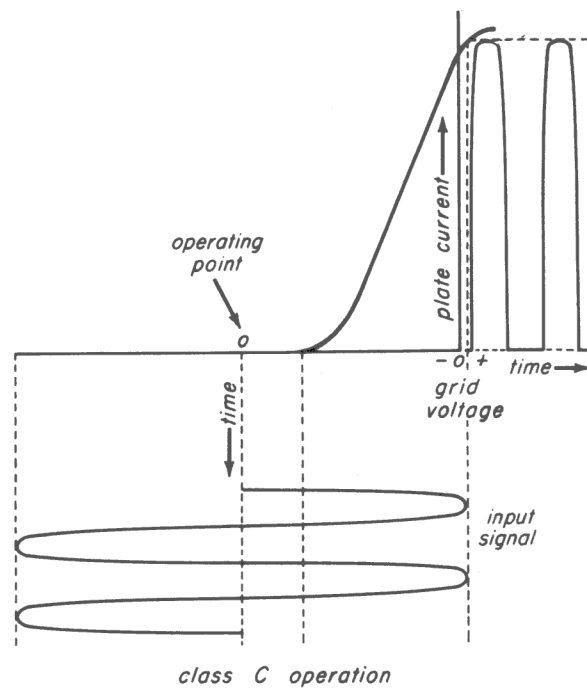


Fig. 23-6

23.2. AUDIO-FREQUENCY VOLTAGE AMPLIFIERS

Voltage amplifiers may be divided into two main classes: audio-frequency amplifiers and radio-frequency amplifiers. Radio frequency amplifiers are discussed in a later lesson. In this lesson, we will give our attention to audio-frequency voltage amplifiers.

Requirements. A voltage amplifier is used to raise the audio-voltage output of the detector to the amount necessary to drive a power-amplifier stage (Fig. 23-7). This increase in signal voltage should be without distortion. In other words, the sound that comes out of the loudspeaker should, as nearly as possible, sound the same as the sound that is picked up by the microphone at the radio or television transmitting station. Therefore, we speak of the *fidelity* of an amplifier. Fidelity is defined as the exactness with which a phonograph, radio, or

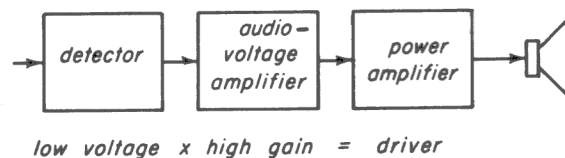


Fig. 23-7

television system reproduces the original sound or picture details. An audio amplifier that has good fidelity must pass all of the frequencies that are picked up by the microphone. The audio range is considered to be from 20 to 20,000 cps. Very little of the audio equipment made can pass frequencies as high as 20,000 cps. However, high-fidelity audio equipment, such as microphones, speakers, amplifiers, and recorders, are considered to have excellent fidelity if they pass frequencies between 30 and 15,000 cps without distortion. Run-of-the-mill receivers are considered to have satisfactory fidelity if they pass from about 200 cps to 8,000 to 10,000 cps. One of the reasons that you may have difficulty in recognizing voices and understanding certain words over your telephone system is that such a circuit normally passes from about 250 cps to about 3,000 cps. As a result, some of the lower frequencies and much of the higher frequencies do not pass through the system.

Types of Distortion. There are three major forms of distortion that may affect the output plate-current waveform of a tube:

1. Nonlinear distortion, which is sometimes called amplitude distortion and which leads to harmonic distortion. Amplitude distortion is due to an unequal amplification of signals of different amplitudes. This distortion results from having the signal voltage on the grid swing into the nonlinear portion of the characteristic curve. This, in turn, is caused by improper grid bias or by too great a signal voltage.

2. Frequency distortion, which results when an amplifier does not amplify all frequencies the same amount. For instance, Fig. 23-8 shows the response curve for an amplifier that amplifies the middle frequencies more than either the low or high frequencies. We will discuss this further later in this lesson.

3. Phase distortion, which is important in video amplifiers but does not materially affect the amplification of audio signals. For this reason, we will not discuss it here and will leave it for discussion in television lessons.

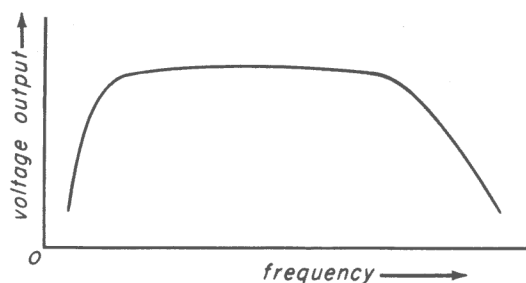


Fig. 23-8

There are other forms of distortion, such as that caused by electrical noises, by hum (ripple voltage), and by loose elements in amplifier tubes (which cause a hum-like ringing noise in the output of the speaker). Another form of distortion is called *intermodulation*, which results when two or more frequencies are applied to the amplifier input. If, for instance, a low note and a high note are amplified at the same time, the distortion in the output of the speaker takes the form of a buzz or a roughness in the notes. However, the first two forms of distortion, nonlinear and frequency, affect audio amplifiers most.

Amplifier Gain. We know that the amplification factor or μ of a tube is a measure of how many times greater a change in plate voltage is than a change of grid voltage. So we can use it to figure how much amplification we can get from a certain tube under certain conditions. However, the amount of actual amplification that a stage produces is always less than μ . It is called the *gain* of the stage, and is the ratio of output signal voltage to input signal voltage. This seems as though it should be the same as μ . The reason that it isn't may be understood if we look at Fig. 23-9a. We see a triode with a load resistor, R_L . The tube is biased by a voltage E_{cc} and receives its plate supply from a voltage E_{bb} . The input

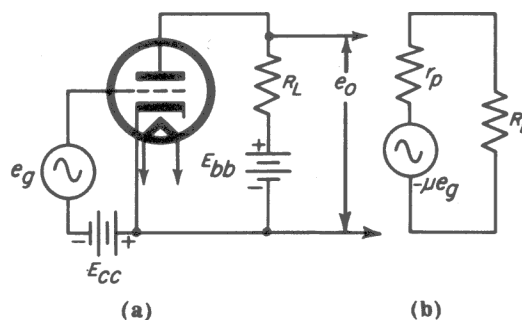


Fig. 23-9

signal voltage on the grid is shown as a generator marked e_g . The output signal voltage (across R_L) is marked e_o . (The electron-tube abbreviations used in this course are shown and defined in Appendix A. These symbols make it possible to write formulas without using many words.)

Since the tube acts like an a-c generator in producing an alternating voltage, it is shown in Fig. 23-9b as an a-c generator with a voltage equal to $-\mu e_g$. This means that, at any instant, the a-c voltage developed in the tube equals μ times the instantaneous value of the signal-input voltage on the grid. The negative sign indicates that the output voltage developed by the tube is 180 degrees out of phase with the input signal voltage. The a-c plate resistance, r_p , compares with the internal resistance of a generator; hence, some of the voltage developed by the tube is dropped inside the tube and the rest across the load. So the figure shows that the output voltage across the load R_L is equal to $-\mu e_g$ less the voltage drop due to r_p . Let's assume that we have a triode with a μ of 20, an r_p of 2,000 ohms, and an R_L of 18,000 ohms. With a signal input of 2 volts, μe_g (we omit the minus sign because the phase of the output voltage does not affect the answer) equals 20×2 or 40 volts. This voltage divides across r_p and R_L in proportion to the resistance that each bears to the total resistance $r_p + R_L$. So, the voltage drop across the plate resistance is:

$$\begin{aligned} e_{rp} &= \frac{r_p}{r_p + R_L} \times \mu e_g \\ &= \frac{2,000}{2,000 + 18,000} \times 20 \times 2 \\ &= \frac{2}{20} \times 40 \\ &= 4 \text{ volts} \end{aligned}$$

While the output voltage across the load re-

sistor equals:

$$\begin{aligned} e_o &= \frac{R_L}{r_p + R_L} \times \mu e_g \\ &= \frac{18,000}{2,000 + 18,000} \times 20 \times 2 \\ &= \frac{18}{20} \times 40 \\ &= 36 \text{ volts} \end{aligned}$$

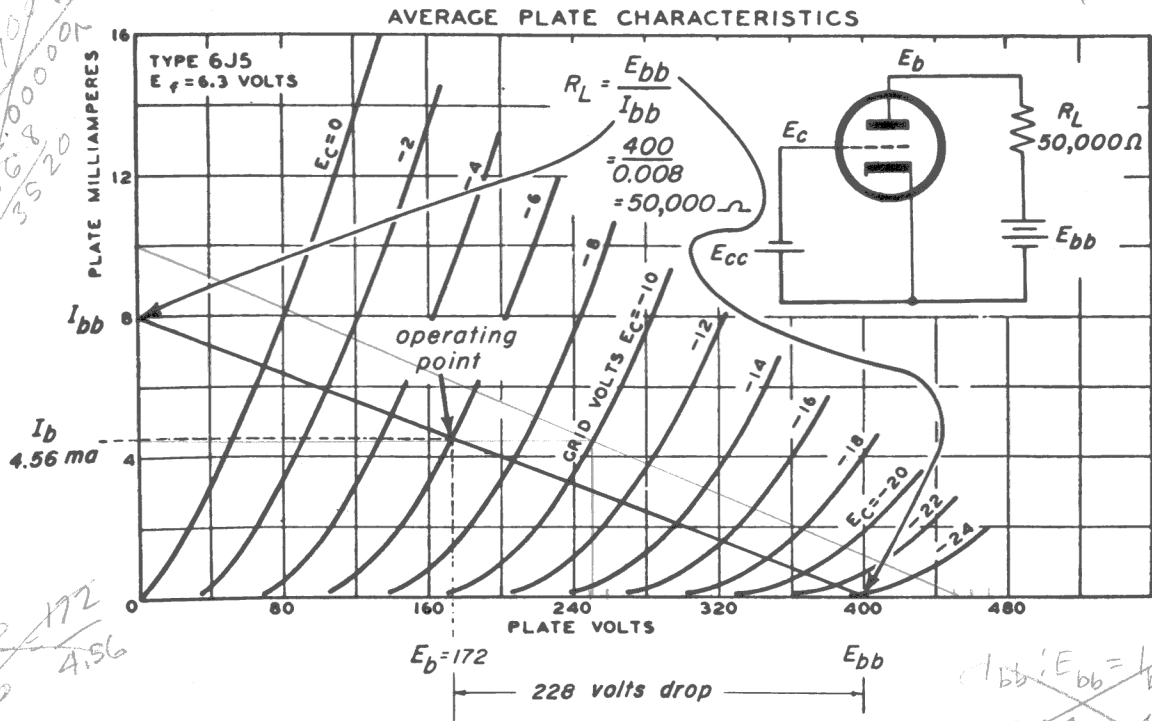
The gain of the stage (the ratio of the output signal voltage to the input signal voltage) is therefore equal to $36/2$, or 18, which means that the signal voltage taken from the load is 18 times the input-signal voltage. If the same tube and input signal are used and the load resistance is increased to 38,000 ohms, the gain becomes 19. With the same tube and input-signal voltage, and with a 78,000-ohm R_L , the gain becomes 19.5. The higher the load resistance (with a fixed r_p), the higher the voltage gain and the nearer it comes to equaling the μ of the tube. However, in practical amplifier-tube circuits, there is a limit to the size of the plate load resistor. For when the value of R_L becomes very great, the d-c voltage drop across it becomes very great too. With a fixed value of E_{bb} , this lowers the value of the operating plate voltage and plate current of the tube. We can show this more clearly if we draw *load lines* on a plate family of curves. But first let's see what a load line is:

23-3. LOAD LINES

Figure 23-10 shows a plate family of curves for the 6J5, reproduced from your RCA Receiving Tube Manual. On this plate family a line is drawn. We call this line a *load line*. A load line may be drawn from any point on the plate-voltage axis to any point on the plate-current axis. The load line in Fig. 23-10 was drawn from the 400-volt point on the plate-voltage axis (marked E_{bb}) to the 8-ma point on the plate-current axis marked I_{bb} . The line represents an amount of resistance that causes a 400-volt drop with a current flow of 8 ma. The value of resistance can be found by using Ohm's law:

Load Lines

7



load line for 50,000 ohm load

Fig. 23-10

$$R_L = \frac{E_{bb}}{I_{bb}}$$

$$= \frac{400}{0.008}$$

$$= 50,000 \text{ ohms}$$

So, a load line represents a value of resistance that produces a voltage drop equal to the supply voltage, E_{bb} , with a current flow equal to that representing the point where the load line meets the plate-current axis, I_{bb} . (I_{bb} is not a standard electron tube abbreviation although it follows the rules for such abbreviations. It is used to prevent confusing it with actual plate-current flow under operating conditions.)

An operating point may be selected almost anywhere in the length of the load line; there are several factors that govern our choice; those factors are discussed a little later in this lesson. For now, we'll assume that we plan to operate the tube with a grid bias of -6 volts. So our operating point is the place where the load line crosses the -6 -volt bias

curve. The operating plate voltage is then found by dropping a line from the operating point perpendicular to the plate voltage axis. This line meets the axis at the 172-volt point; so $E_b = 172$ volts. The voltage drop due to the load resistor is the difference between E_{bb} (400 volts) and E_b (172 volts) and is equal to 228 volts. It can also be found if we know how much plate current flows when $E_b = 172$ volts and $E_c = -6$ volts. We find the plate current flow by drawing a line from the operating point perpendicular to the plate-current axis. This voltage may now be found:

$$E_{bb} - E_b = I_b \times R_L$$

$$= 0.00456 \times 50,000$$

$$= 228 \text{ volts}$$

Now let's see if we can use the load lines to prove, with a fixed value of E_{bb} and E_c , that as the load resistance rises in value, E_b and I_b fall. Figure 23-11 shows four load lines drawn on the 6J5 plate family, representing four different load resistances. In order to make the arithmetic simple, these lines were drawn from the 240-volt point on

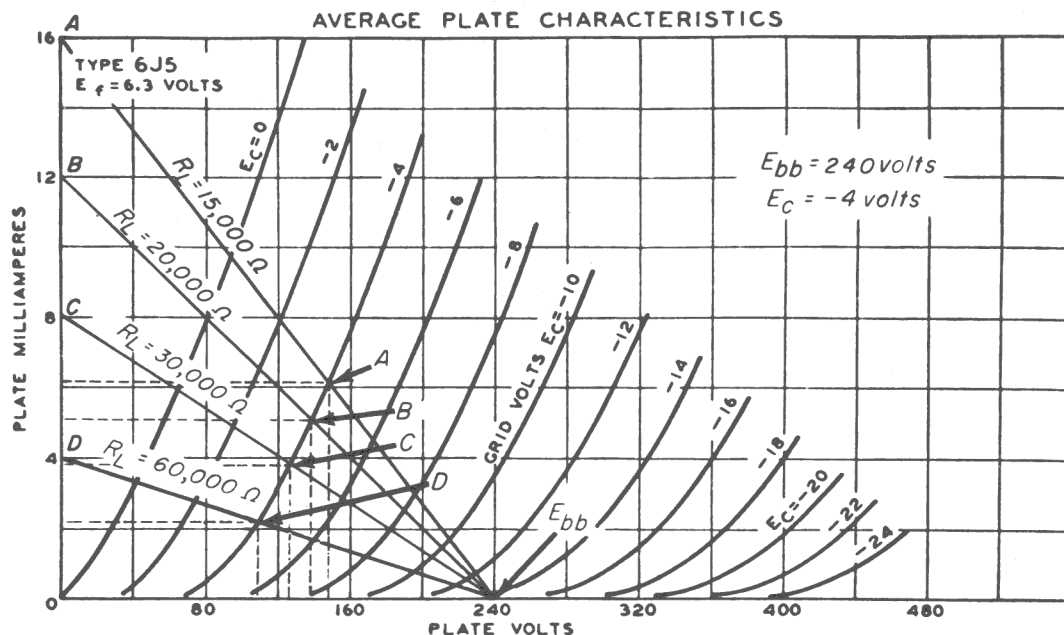


Fig. 23-11

the plate-voltage axis to points on the plate-current axis that represent numerical values of current that are easy to work with. The load lines for practical amplifier tubes are not always found with such simple figures, as you will see later on.

The uppermost load line was drawn from a point on the plate-current axis representing a current flow of 16 ma. The value of resistance needed to drop 240 volts, with a current flow of 16 ma, is found by Ohm's law:

$$\begin{aligned}
 R &= \frac{E_{bb}}{I_{bb}} \\
 &= \frac{240}{0.016} \\
 &= 15,000 \text{ ohms}
 \end{aligned}$$

Using the same method, the other load lines were drawn from the same voltage point to the 12-ma, 8-ma, and 4-ma points on the plate current axis. Using Ohm's Law, the resistance values were found to be as shown on the drawing.

In order to see how the plate voltage and current change with the value of load resistance, we set up an operating point on each load by keeping the grid voltage E_c constant at -4 volts. Point A on the 15,000-ohm load line represents a plate voltage

E_b of 147 volts and a plate current I_b of about 6.2 ma. Point B on the 20,000-ohm load line represents an E_b of 138 volts and an I_b of 5.2 ma. Point C indicates 125 volts and 3.7 ma on the 30,000-ohm load line and point D shows 108 volts and 2.3 ma on the 60,000-ohm load line. In this way, you can see that, with a fixed E_{bb} , a rise in load resistance produces a reduction in E_b and I_b .

Notice that each of these load lines has a different slant. We call this slant the *slope* of the load line, and it becomes less steep as R_L rises. The slope of the load line is important. A rule of thumb says that for power amplifiers the slope should be steep, and for voltage amplifiers the slope should be much less steep. However, the same tube cannot usually be operated as both a voltage amplifier and a power amplifier.

A rise in value of R_L need not necessarily mean a lowering of value of E_b . Figure 23-12 shows four load lines drawn between the 8-ma point on the plate-current axis at four different points on the plate-voltage axis. The same operating bias was selected as before, so the point where each load line crosses the -4 volt grid curve becomes the operating point for the R_L it represents. Therefore, A is the operating point for a 60,000-ohm load resistance with an E_{bb} of

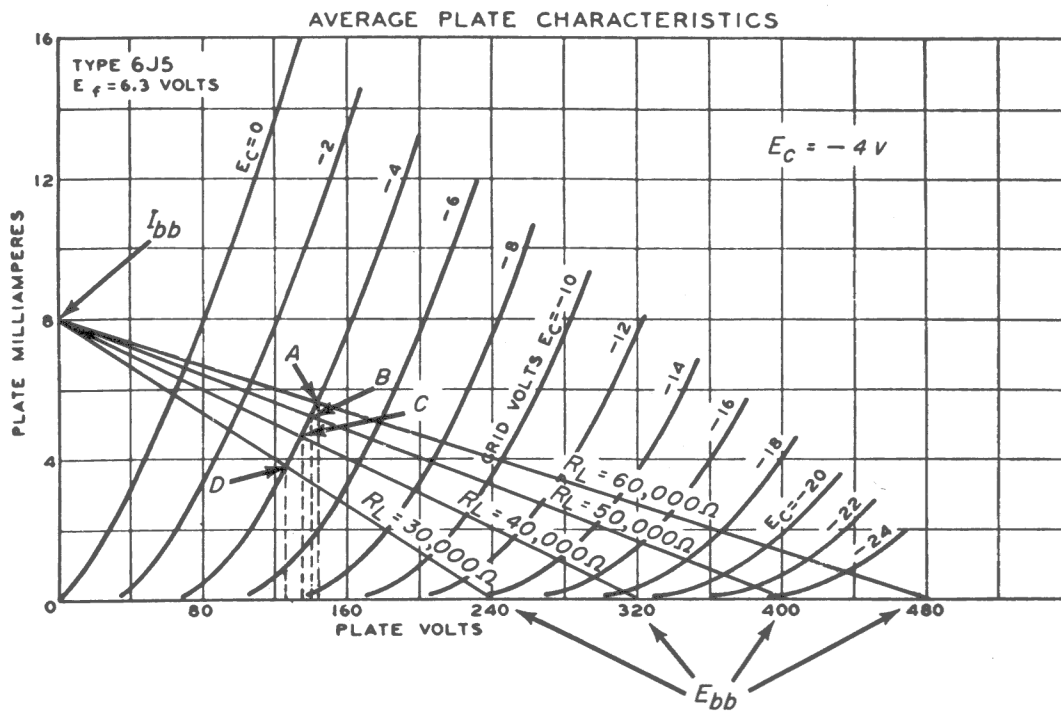


Fig. 23-12

480 volts. B is the operating point for a 50,000-ohm resistance and an E_{bb} of 400 volts, and so on. In this case, the plate voltage E_b , rises slightly as the resistance of the load rises. Figure 23-12 tells us one important thing: with the higher values of R_L , higher values of E_{bb} are needed to provide about the same E_b . In fact, we may

easily obtain the same operating plate voltage by selecting as our operating point on each load line the point where the load line crosses the plate-voltage value we wish to select. For example, we could select 160 volts as E_b , which would give us the operating points shown in Fig. 23-13. In such a case, however, the grid bias would vary with each load line.

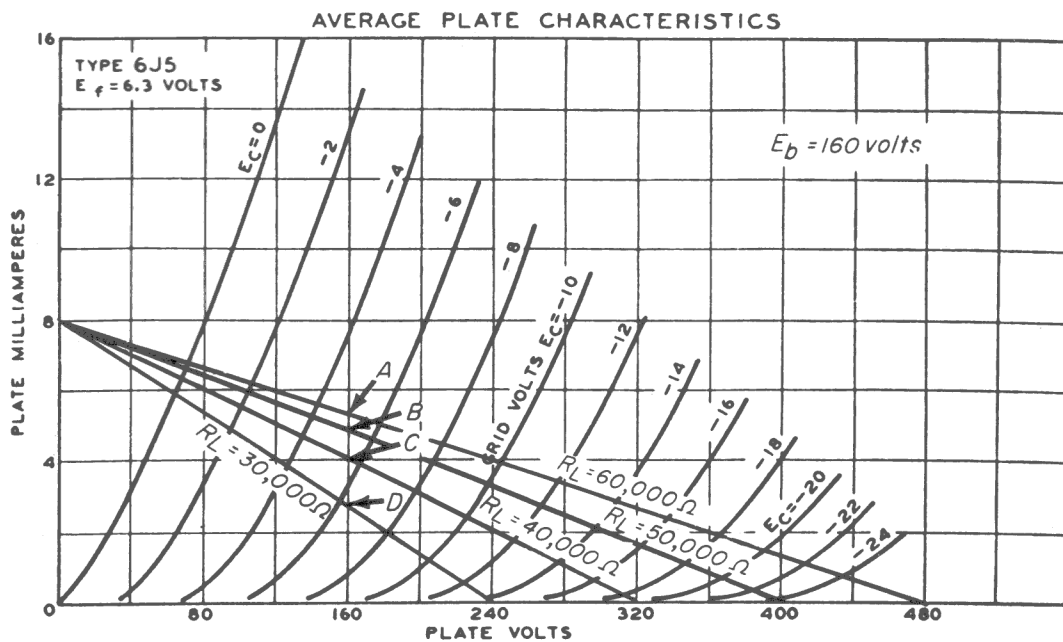


Fig. 23-13

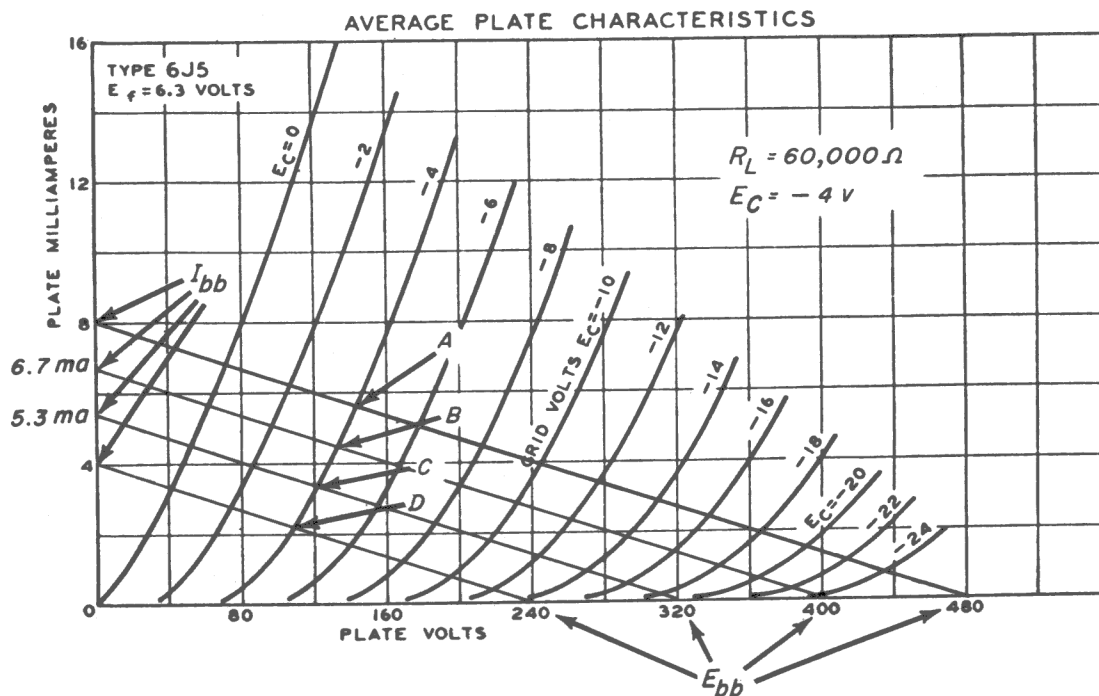


Fig. 23-14

When two or more load lines have the same slope, as in Fig. 23-14, they represent the same value of load resistance. Each of the load lines in the drawing represents a load resistance of 60,000 ohms, drawn from different values of E_{bb} . Each operating point calls for -4 volts of grid bias, while the E_b ranges from about 108 to 144 volts. We have said that the slope of a load line affects its use in voltage amplification. All of the load lines of Fig. 23-14 have the same slope, so what difference does it make which we use? This, and other questions that may have occurred to you will be answered as you study the use of load lines.

Use of Load Lines. Now that we know how to construct load lines, and have studied some of their characteristics, let us see how they can be put to use. By plotting an input signal on the plate characteristics curve, upon which the load line has been drawn, the amplitude and exact waveshape of the output signal can be obtained. Let us assume we are applying an 8-volt peak-to-peak signal to the circuit shown in Fig. 23-15. Since the plate load is 60,000 ohms, and the B supply voltage is 480 volts, the load line is exactly the same as load line A in Fig. 23-14. Without any input signal, the operating point is designated as point O in Fig. 23-15. Now the 8-volt peak-to-peak sig-

nal is applied in series with the grid bias, so that the total grid to cathode voltage instantaneously varies from zero volts to -8 volts. The 8-volt peak-to-peak signal is drawn on the diagram using the -4 volt line as a starting point. The positive half-cycle of the signal extends to zero volts, and the negative half-cycle of the signal extends to -8 volts. Thus the signal applied makes the instantaneous operating point move back and forth along the load line between points 1 and 2. When the input signal is at zero, the voltage on the grid is -4 volts, the plate current, I_b , is 5.6 ma, and the plate voltage, E_b , is 144 volts. As the input signal rises to its positive maximum, the voltage on the grid becomes less negative until it reaches zero. While this occurs, the plate current rises until it reaches a maximum ($i_{b \max}$) of 6.8 ma, and the plate voltage drops to a minimum ($e_{b \min}$) of 71 volts. As the input signal voltage decreases from its positive maximum, falls to zero, and rises to its negative maximum, the grid voltage becomes more and more negative until it reaches a negative maximum of -8 volts. As this occurs, the plate current falls from its maximum, 6.8 ma, to its minimum ($i_{b \min}$) of 4.4 ma and the plate voltage rises from its minimum of 71 volts to its maximum ($e_{b \max}$) of 214 volts. Completing one cycle, the input signal voltage returns to

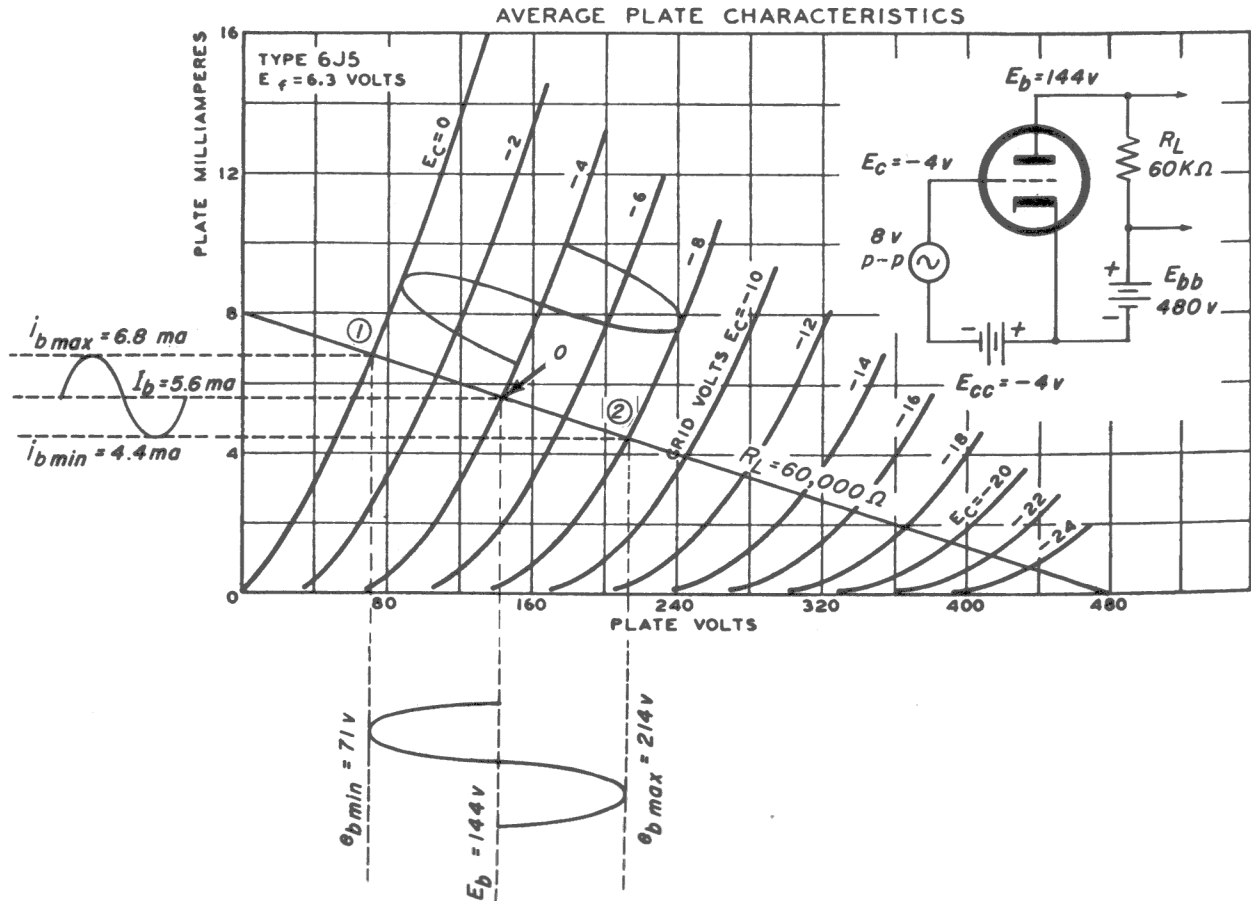


Fig. 23-15

its zero value, the grid voltage returns to -4 volts, the plate current to 5.6 ma , and the plate voltage to 144 volts. A swing of 8 volts on the grid causes a total plate current change of 2.4 ma and a total plate voltage change of 143 volts. The gain:

$$A = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{143}{8} = 18 \text{ (approx)}$$

Of course, the gain and output voltage could also have been found by the procedure of Section 23-2. However, the load line method gives us not only the gain and output voltage, but the exact shape of the output curve. The importance of this can be seen by applying the same input signal as before to the circuit of Fig. 23-16. Here, R_L has been reduced, and E_{bb} is also lower. Again the 8 -volt peak-to-peak signal in series with the bias of

-4 volts changes the grid voltage from 0 to -8 volts. The corresponding changes in plate voltage and plate current are shown on the diagram. What are the differences in operation between the two circuits? Note first of all that the output voltage is only 105 volts, and that the gain is therefore

$$A = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{105}{8} = 13$$

which is lower than before. Note also, and this is most important, that the output waveshape is distorted. A close inspection of the output waveshape will show that the bottom half is smaller than the top half. If this is not obvious from the drawing, then note that the increase in current is greater than the decrease in current; and that the decrease in plate voltage is greater than the increase in plate voltage. We can calculate the amount of second harmonic distortion* from the formula:

* See Appendix.

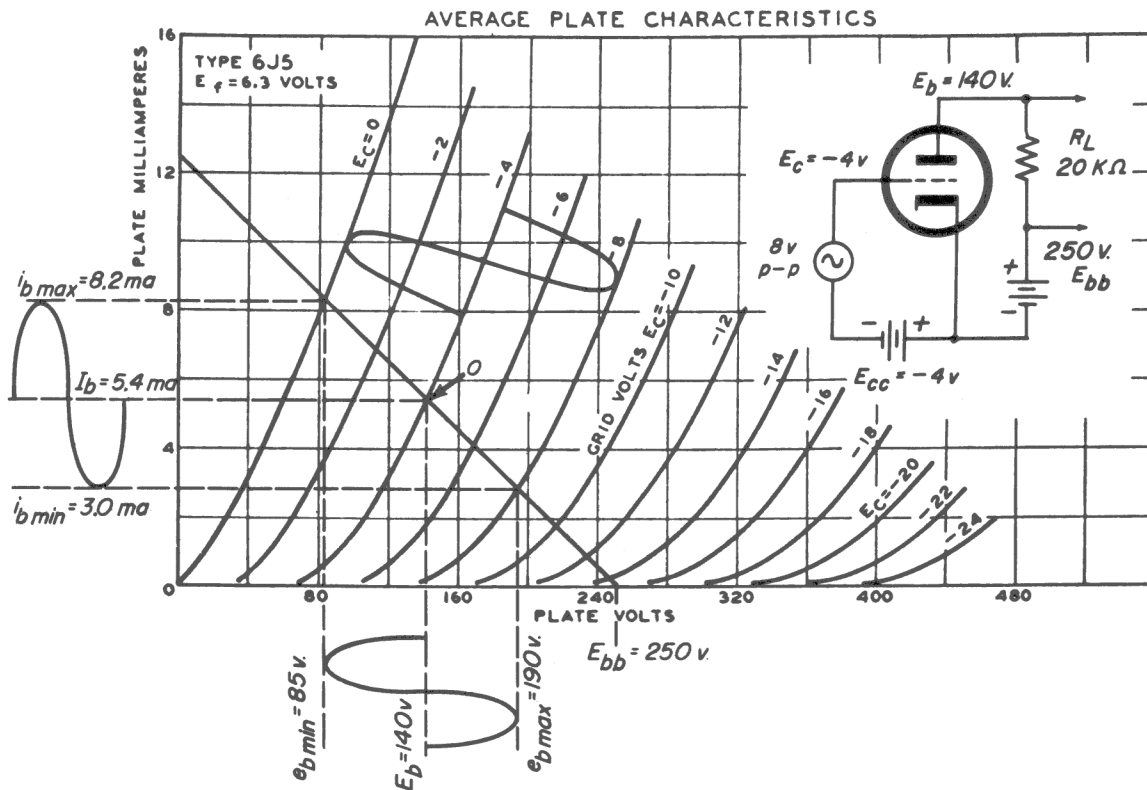


Fig. 23-16

$$\% \text{ 2nd-harmonic distortion} = \frac{i_{b \max} + i_{b \min} - I_b}{i_{b \max} - i_{b \min}} \times 100$$

where:

$i_{b \max}$ = maximum instantaneous value of plate current

$i_{b \min}$ = minimum instantaneous value of plate current

I_b = zero-signal plate current

and in this case find it to be

$$\begin{aligned} & \frac{\frac{8.2 + 3}{2} - 5.4}{8.2 - 3} \times 100 \\ &= \frac{5.6 - 5.4}{5.2} \times 100 = \frac{0.2}{5.2} \times 100 = 4\% \text{ (approx)} \end{aligned}$$

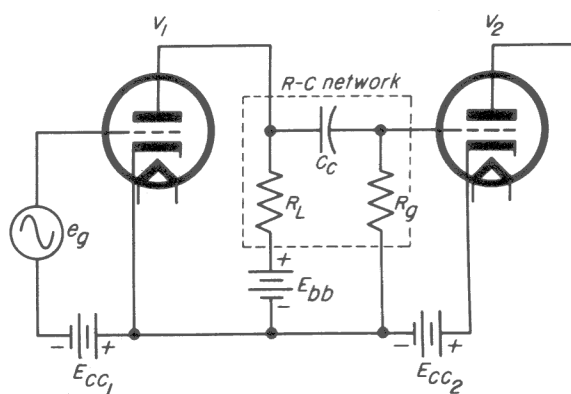
Distortion greater than 5% is usually very noticeable, and the amount of distortion is not allowed to be greater than this figure in most audio amplifiers. In high-fidelity amplifiers the distortion is kept much lower than

this, and may be less than 1%. Distortion is not usually a problem in voltage amplifiers because the input signals are usually much smaller than the 8-volt peak-to-peak signal used as an example here. This large signal was used to make the drawings clear. The smaller the signal the smaller the amount of distortion produced.

We can now state as a general rule that for voltage amplifiers, the load should be as large as needed to obtain the required gain and the B supply should be high enough to keep the part of the load line in use out of the curved portions of the characteristic curves. Also, it will be shown in later lessons that the larger the load resistor the narrower the frequency response of the amplifier stage. We can summarize by saying that increasing the load resistance increases the gain, but narrows the frequency response, and may require an increased B supply to keep the load line out of the curved portion of the characteristic curves.

23-4. AMPLIFIER COUPLING

The output of a voltage amplifier is usually fed to either another voltage amplifier or



R-C coupled amplifier

Fig. 23-17

to a power amplifier. When this is done, we say that the first amplifier is *coupled* to the second amplifier in *cascade*. Several methods are used to couple one amplifier to another. They are: *R-C coupling*, *impedance coupling*, *transformer coupling*, and *direct coupling*. We will now compare these methods.

R-C Coupling. The coupling shown in Fig. 23-17 is called resistance-capacitance (R-C) coupling, or sometimes just resistance coupling. The coupling network consists of the plate load resistor, R_L , for the first tube, the *coupling capacitor* (sometimes called the *d-c blocking capacitor*, C_c , and the grid-load resistor, R_g , for the following tube. The plate-load resistor, R_L , is high compared with the plate resistance, r_p . In R-C coupled amplifiers, R_L may have a resistance value of from 50,000 to 500,000 ohms. R_g will then have a resistance value of from 1 to 5 times that of R_L . The coupling capacitor, C_c , makes it possible to pass the signal voltage from R_L to R_g without permitting the d-c potential from reaching the grid of the second tube. For that reason, the capacitor must be large enough so that it does not offer much reactance to the audio signal voltages being passed. Coupling capacitors range in value from 0.001 μf to 0.25 μf .

Let us further study the nature of the coupling of an R-C coupled amplifier. We know that the output signal voltage of V_1 appears across R_L . It is this output voltage we want to couple to R_g . Although the out-

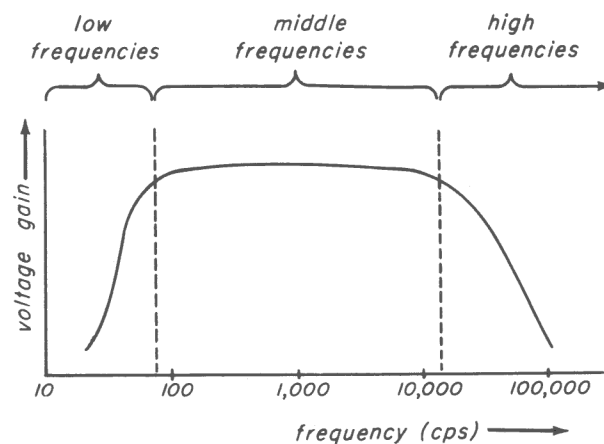
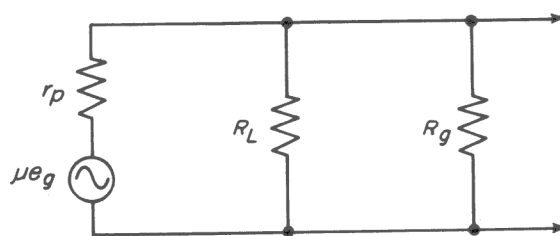


Fig. 23-18

put voltage is developed across R_L , it can be taken off plate and cathode. Ordinarily, the impedance of a power supply, such as E_{bb} for V_1 , is low, ideally zero. If the power-supply resistance were zero, there could be no a-c signal voltage drop across it. Thus, a-c signal output voltage appears between plate and cathode (and is the same as appears across R_L). Notice that one end of R_g is connected to the plate through C_c and the other end to the cathode. Appearing across R_g is the signal output voltage of V_1 . This voltage now becomes the input voltage for V_2 .

Figure 23-18 shows a response curve for a typical R-C coupled amplifier. Frequency is plotted on the X axis and the amount of gain on the Y axis. Note that the middle frequencies are amplified more than the lower or higher frequencies. We say that the amplifier discriminates against the lower and higher frequencies. Figure 23-19 shows the equivalent circuit, at the middle frequencies, of the R-C amplifier that was shown in Fig. 23-17. Because the coupling capacitor offers practically no reactance to



equivalent circuit at middle frequencies

Fig. 23-19

these frequencies, it is not shown in the equivalent circuit. Therefore, whatever voltage appears across R_L appears across R_g . In fact, the plate load of the first triode, V_1 , is the equivalent resistance of R_L in parallel with R_g . The gain for the middle frequencies is found by the formula:

$$A = \frac{\mu Z_o}{r_p + Z_o}$$

where:

A = gain

$Z_o = R_L$ and R_g in parallel

r_p = plate resistance

μ = amplification factor

For example, a 6J5 has a μ of 20 and an r_p of 7,700 ohms when operated with an E_b of 250 volts. R_L is 50,000 ohms and R_g is 100,000 ohms. First we must find Z_o :

$$\begin{aligned} Z_o &= \frac{R_L \times R_g}{R_L + R_g} \\ &= \frac{50,000 \times 100,000}{50,000 + 100,000} \\ &= \frac{5,000,000,000}{150,000} \\ &= 33,300 \text{ ohms} \end{aligned}$$

Then we find the gain:

$$\begin{aligned} A &= \frac{\mu Z_o}{r_p + Z_o} \\ &= \frac{666,000}{41,000} = 16.2 \end{aligned}$$

This middle frequency gain is considered to be the gain for the stage. However, the gain at the low end and the high end of the band of frequencies passed by the amplifier is not as high as the mid-frequency gain. Let's see why this is so.

We know that the reactance of a capacitor rises as the frequency drops; for the lower frequencies, the coupling capacitor offers more reactance. Therefore, for the low fre-

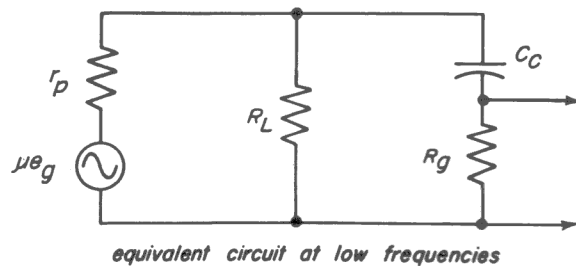


Fig. 23-20

quencies, we cannot leave the reactance of the coupling capacitor out of our figuring. Figure 23-20 shows the equivalent circuit of the R-C amplifier for low frequencies. It shows that C_c and R_g are actually in series and that R_L is in parallel with them. So, the amplified signal voltage that appears across R_L divides: part across C_c and part across R_g . The amount of voltage that appears across the capacitor depends on the frequency and the capacity of C_c . For a given value of C_c , as the frequency decreases, the reactance of C_c increases, and results in less voltage drop across R_g . For a given frequency, the larger C_c is, the smaller is its reactance and results in more voltage across R_g . Thus, it can be seen that the coupling capacitor, C_c , reduces the gain for low-frequency signals.

We know that the reactance of a capacitor drops as the frequency rises, so the reactance C_c offers to the passage of high frequencies is not important. However, other capacities that are too small to be considered at the low and middle frequencies become very important at high frequencies. The simplified drawing in Fig. 23-21 shows that the stray capacitances that exist in the wiring and circuit parts act together as a shunt across the plate and grid load resistors. In addition, the capacity that exists between the cathode and grid of triode V_2 is also shunting the load. As a result, the

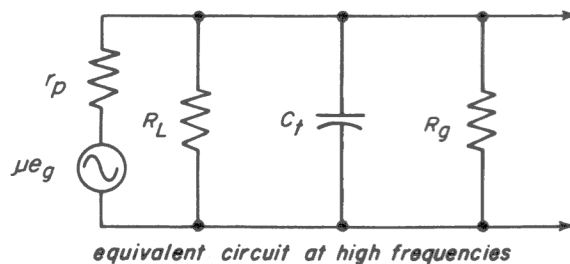
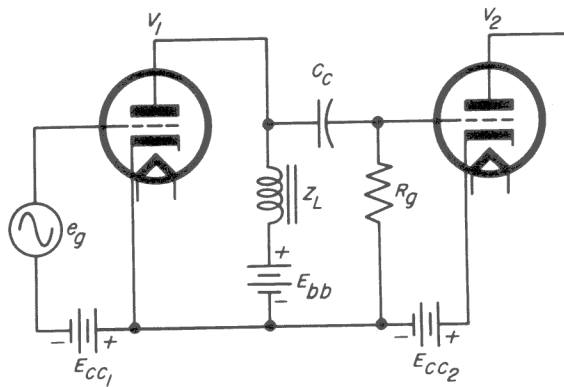


Fig. 23-21



impedance-coupled amplifier

Fig. 23-22

total shunt capacitance C_t offers a low-reactance path for high frequencies, which reduces the amount of signal voltage that is fed to the grid of the triode V_2 .

Impedance Coupling. One disadvantage of R-C coupling for high-gain amplification is that a large value of R_L produces a large drop between the B supply voltage, E_{bb} , and the d-c voltage, E_b , actually applied to the plate. This requires the supply voltage to be much higher than is necessary when an iron-core choke replaces R_L , as in Fig. 23-22. The d-c resistance of such a choke is small, so that the d-c voltage drop is small and E_{bb} needs be only slightly higher than the B voltage applied to the plate. At the same time, the reactance of the choke is high enough for the middle frequencies to provide high gain. However, at low and high frequencies, the gain drops off, as shown by the response curve in Fig. 23-23. The reactance of the choke is low for low frequencies, so less of the amplified signal voltage appears across the choke and more is dropped across the plate resistance r_p . At high frequencies, the dis-

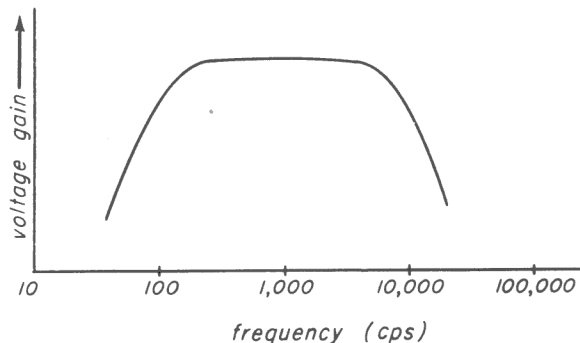


Fig. 23-23

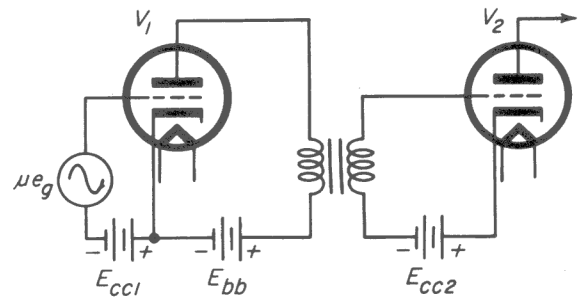


Fig. 23-24

tributed capacitance between the turns of the choke, the interelectrode capacitances of the tubes, and the stray capacitance of the parts and wiring produces a reactance in shunt with the load that becomes smaller as the frequency rises. This causes the effective impedance of the load to drop and reduces the value of the signal voltage that appears across it.

Impedance coupling is not used often in modern radio and television receivers. However, before high-mu tubes were developed, some receivers did use impedance coupling. For that reason, it was discussed in this lesson.

Transformer Coupling. As shown in Fig. 23-24, the output of V_1 may be coupled to V_2 by means of a transformer, which in this cases, is called an *interstage audio transformer* because it connects one stage (a tube and its circuit) with another. When such a transformer is used in a radio or television receiver's audio system, it usually couples a stage of voltage amplification to a stage of power amplification. Transformer coupling has advantages that we do not find with R-C or impedance coupling. For one, we find that we can get greater gain through transformer coupling than from either R-C or impedance coupling because the signal voltage that appears across the transformer primary is stepped up by using a step-up turns ratio from the primary to the secondary winding. In this way, the voltage gain is not limited to about the μ of the tube. As in impedance coupling, the plate-supply voltage does not have to be as high as it is for R-C coupling. In addition, transformer coupling has two important advantages that will be discussed fully in the lesson on power amplifiers. These are: transformers

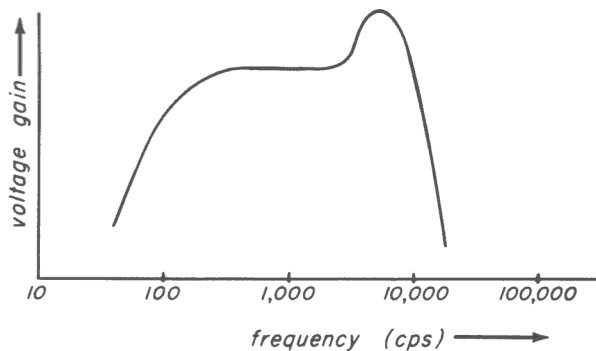
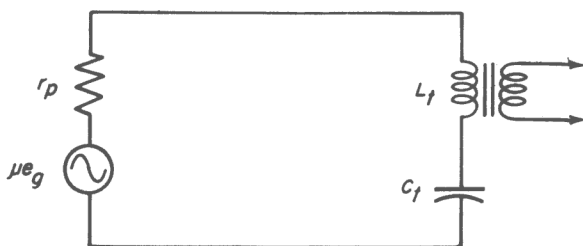


Fig. 23-25

permit better matching of one amplifier tube to another; and the secondary may be center tapped so that two power tubes may be coupled to the same voltage amplifier.

However, transformer coupling has some disadvantages. The response curve of Fig. 23-25 shows that a transformer discriminates against low and high frequencies. The low reactance that the primary offers to low frequencies reduces the amount of signal voltage that appears across the primary and, therefore, the amount of signal voltage that can be induced into the secondary. The distributed capacitance of the transformer windings combines with the total inductance of the transformer, as in the equivalent circuit shown in Fig. 23-26, to form a series tuned circuit that resonates at some high frequency. This causes a rise in signal voltage at or near the resonant frequency. For frequencies above the resonant frequency, the reactance of the distributed capacitance decreases and the voltage output decreases. In addition, even the less expensive types of audio transformers cost much more than the resistors and capacitor that go to make up an R-C coupled amplifier.

The frequency response of an audio transformer may be improved by using high-in-



equivalent circuit of transformer-coupled amplifier at high frequencies

Fig. 23-26

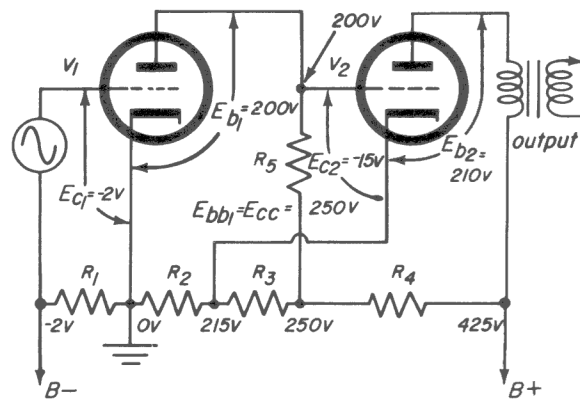


Fig. 23-27

ductance windings so that the transformer receives a greater portion of the amplifier low-frequency voltage. The stray capacitances of such a transformer must be kept to a minimum. High-fidelity transformers, as these are called, permit better low- and high-frequency response. However, they are usually expensive and take up a great amount of space on the receiver chassis.

Direct Coupling. Until now, we have considered only the coupling systems that keep the plate of one tube at a different d-c potential than the grid of the following tube. Such systems block d-c and permit only the a-c signal voltage to pass on to the next tube. Most of the audio amplifiers found in modern radio and television receivers belong to this group of systems. However, there is one system of coupling that connects the plate of one tube directly to the grid of the following tube. For that reason, it is called *direct coupling*. It is sometimes abbreviated *d-c coupling*. In this case, d-c stands for *direct coupled* and must not be read as *direct current*. A typical direct-coupled amplifier circuit is shown in Fig. 23-27. We have found that the d-c plate voltage of a triode (E_b) must be positive with respect to the cathode if plate current is to flow. We know, too, that the d-c voltage on the grid is usually negative with respect to the cathode. In fact, all electron-tube potentials are relative to the cathode, which means that they are measured between cathode and each operating electrode or element. (The only exception to this is the heater of an indirectly heated cathode, which is not considered to be a tube element.) With this in mind, let us look at Fig. 23-27 again.

The voltages that are applied to the electrodes of the tubes are obtained from the voltage divider of the power supply. The total power-supply voltage is 427 volts. The right end of the resistor is grounded (0 volts) and serves as a reference point. This point is connected to the cathode of V_1 . The left end is negative by two volts. Since this end is connected to the control grid of V_1 , the grid is biased by -2 volts. The resistor R_5 serves as a plate load resistor of V_1 . The d-c voltage drop across R_5 is 50 volts. Since the lower end of R_5 is connected to a $+250$ volts source at the junctions of R_3 and R_4 , the plate-to-cathode voltage for this tube is 200 volts. Furthermore, this $+200$ volts appear at the grid (with respect to ground) of V_2 . However, note that the cathode of V_2 is connected to a $+215$ volts source (junction of R_2 and R_3). Thus, the voltage between grid and cathode is -15 volts. Because the control grid is *less positive* than the cathode by 15 volts, it is the same as if the grid were -15 volts and the cathode were at 0 volts. A meter connected between the grid and cathode of V_2 would show that the grid is 15 volts negative with respect to cathode.

Neglecting the d-c voltage drop across the primary of the transformer, the plate of V_2 is connected to a $+425$ volt source. Remember that the cathode is connected to a $+215$ -volt source. Hence, the plate-to-cathode voltage (E_{b2}) is 210 volts. From this we can see that the operating potentials between the tube elements are normal. However, the total B supply voltage must be higher for direct-coupled amplifiers than it is for any of the systems we have studied until now.

Direct-coupled amplifiers provide low and mid-frequency amplification without phase or frequency distortion. For that reason, they are used for low-frequency amplifiers. However, the interelectrode capacitances of both tubes, particularly the C_{pk} of V_1 and the C_{gk} of V_2 , produce a shunt capacitance that reduces the high-frequency gain. To sum up, a direct-coupled amplifier provides practically distortion-free amplification for low frequencies when the tubes are operated in the linear portion of the characteristic curve.

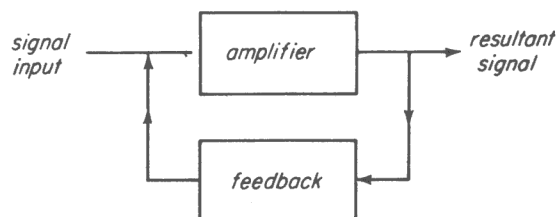


Fig. 23-28

23.5. FEEDBACK IN AUDIO AMPLIFIERS

Part of the amplified signal voltage may be fed back from the output of an amplifier, as shown in Fig. 23-28. In other words, a portion of the output signal voltage that appears in the plate load of an amplifier tube may be fed back to the grid of the same tube or to the grid of a previous tube. Such feedback may take one of two forms. If the feedback voltage aids or adds to the signal voltage being fed to the grid of a tube, it is called *positive* or *regenerative* feedback (shown in Fig. 23-29a). If the feedback voltage opposes or subtracts from the signal voltage applied to the grid, it is called *negative*, *inverse*, or *degenerative* feedback (Fig. 23-29b).

A positive feedback voltage is in phase with the signal voltage being amplified and so increases the effective voltage gain of the tube. At the same time, it increases any noise or distortion that may be due to the tube. Regenerative feedback may cause squeals and howls in the audio output. When you study oscillator theory, you will find that this is because the tube is acting as an oscillator. At that time, you will also find that oscillators use some form of positive feedback to produce voltages at wanted

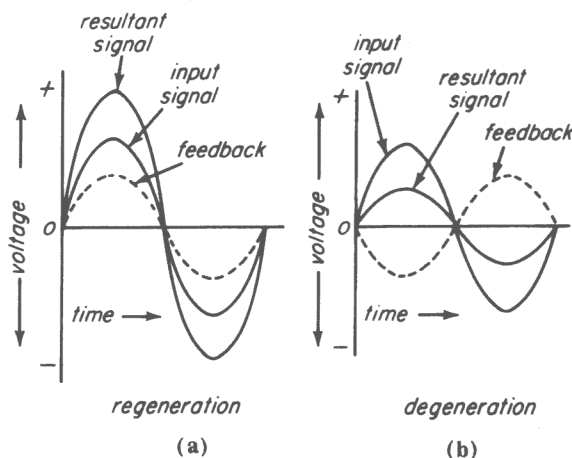


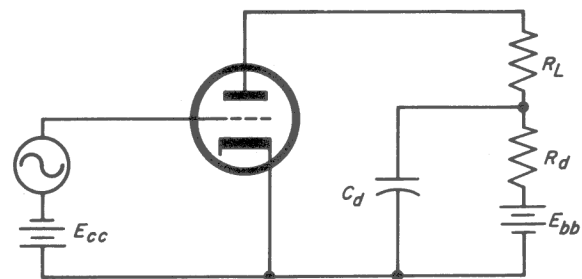
Fig. 23-29

frequencies. Figure 23-29*b* shows that degenerative feedback is 180 degrees out of phase with the signal voltage being amplified, so that the feedback voltage cancels out a portion of the signal and so reduces the effective gain of the tube.

Positive feedback or regeneration is seldom purposely used in audio amplifiers. However, there are several ways in which positive feedback may occur. In our study of triodes, we learned that some of the amplified signal voltage may be fed back from the plate to the grid by means of the interelectrode capacitance that exists between these two elements (C_{gp}). It was partly to reduce the possibility of such feedback that the tetrode and pentode tubes were designed. For, in each of these types, the screen grid acts to reduce the amount of interelectrode capacitance, thus reducing the amount of possible feedback. However, there are other ways in which a portion of the amplifier signal voltage may be fed back to the amplifier input. The signal may be fed back through the stray capacitance that exists between the input (grid) and output (plate) circuits. For example, a grid lead may run close to the coupling capacitor or to a plate lead. If an interstage transformer is used, it may be so placed that it picks up some of the amplified signal from the output transformer. This can happen when one transformer is in the field of another.

Several methods are used to prevent feedback. One method is to wire components and run wiring so that the grid and plate components and wiring are not near each other. Another is to use metal shielding on grid and plate leads and to ground the shield to the chassis. If transformers are used, see that they are properly shielded and placed so that one transformer is not placed in the field of another. If two transformers must be placed close to each other, their windings should be placed at right angles to each other for minimum mutual inductance.

There remains one very important source of feedback in amplifiers—the common *B* power supply. When two or more amplifier tubes receive power from the same power source, a portion of the amplified signal voltage may be fed back to an earlier stage

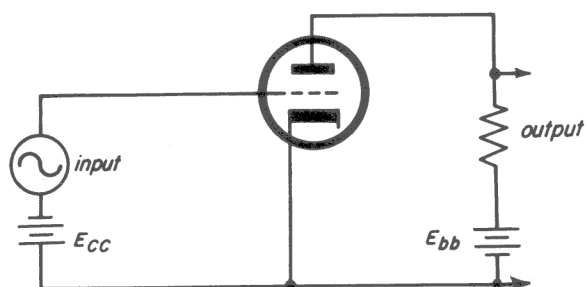


amplifier with decoupling filter

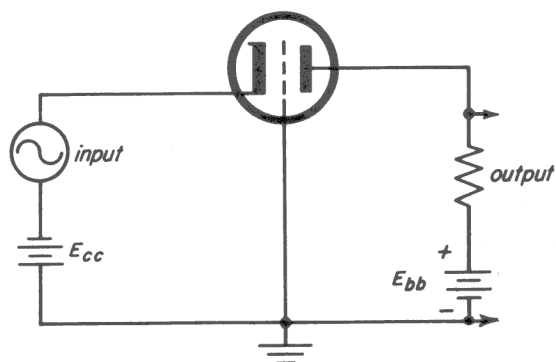
Fig. 23-30

through the power supply. Such feedback may be avoided by the use of a *decoupling filter*. Figure 23-30 shows a typical decoupling filter used to decouple the plate circuit of an amplifier from the common *B* supply. The decoupling resistor, R_d , is usually about $1/5$ the value of R_L . The decoupling capacitor, C_d , must be high enough so that its reactance at the lowest audio frequency to be passed is very much less than the resistance of R_d . In practice, the reactance of C_d at the lowest audio frequency to be passed should be one-tenth the resistance of R_d . In a typical audio amplifier, C_d may range in value from 0.25 to 20 μf . When a decoupling filter is used, the value of the supply voltage, E_{bb} , must be increased to make up for the voltage drop across the decoupling resistor. If such additional voltage is not available, a filter choke may be used in place of the resistor. However, a choke takes up much more room and costs considerably more than a resistor, so it is usually better to try to increase the *B* supply voltage than to use a choke.

Degenerative-Feedback Amplifiers. In the amplifiers discussed so far, the cathode has been the common point between the input and output circuits of the tube. The input signal has been applied between the grid and cathode, while the amplified output signal has been taken from a load impedance placed between the plate and cathode (Fig. 23-31*a*). It is not necessary that we have such an arrangement. Figure 23-31*b* shows a *grounded-grid* amplifier, in which the grid is common to both the input and output circuits. Even in such a circuit, the plate current must flow through the cathode. Therefore, some of the amplified a.c. flows through the input-signal impedance. This produces an alternating voltage drop across the input impedance that



(a) cathode is common to input and output



(b) grid is common to input and output

Fig. 23-31

is 180 degrees out of phase with the input signal voltage. This produces degeneration. Such amplifiers are used mainly in the amplification of frequencies above 100 megacycles and, for that reason, will not be discussed further here. It is mentioned here only as an alternate method of feeding a signal into a triode.

Another circuit, called a *cathode follower* (Fig. 23-32) uses the plate as the common electrode. The signal is injected between grid and ground and the output is taken between cathode and ground. One important difference between this circuit and the others

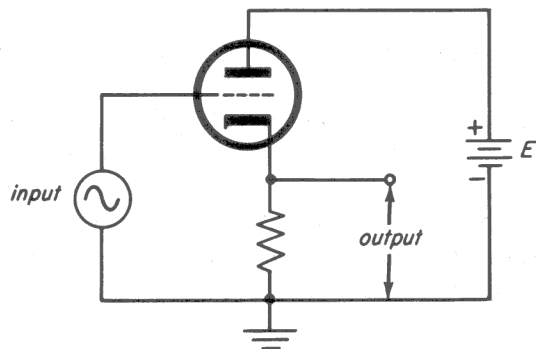


Fig. 23-32

we have discussed is that the load resistance is between ground and cathode. The entire output voltage actually subtracts from the input voltage, so that this is a degenerative feedback circuit where the voltage gain is less than 1. However, we may obtain a power gain from such a circuit. One application of the cathode-follower is discussed in Theory Lesson 24.

Controlled Negative Feedback in Amplifiers. Sometimes, in audio-amplifier circuits, it is desirable to introduce a certain amount of negative feedback in order to obtain some worthwhile end, even though it may cause a reduction in total gain. It may be used to reduce noise, hum, or distortion. It may be used to increase fidelity. In order to make up for any loss in gain caused by negative feedback, it may be necessary to use a tube with higher μ than you need or to use an extra stage of amplification. Negative feedback circuits are discussed more completely in Theory Lesson 25.

23-6. PUTTING CURVES TO USE

Unless you become a design engineer, it is not likely that you will ever need to know how to design any or most of the circuits that are found in radio or television receivers, and if you do, it will be necessary for you to take courses in design engineering first. However, of the basic types of circuits found in radio and television receivers, you are more likely than not to experiment with audio amplifiers. You probably won't design a complete amplifier from scratch, but it is likely that you will, at one or more times in your career, assemble an amplifier according to the instructions of some engineer or audio fan given in a magazine article. In such cases, you will have few design problems because practically everything will have been worked out for you. The value and, in some cases, the brand and part number of each part of the amplifier will be given in the magazine article. Yet, from this lesson and the next few lessons, you should learn enough about amplifiers, particularly audio amplifiers, to design a simple one for your-

self. With the experience gained from such an undertaking, you may find yourself trying out your ideas on more difficult audio circuits. The purpose of this section of the lesson is to show you how you may use curves to provide you with the answers for certain definite problems.

To begin with, let's assume that we have a power supply with a limited amount of B voltage, yet we wish to obtain as much voltage gain as possible with an allowable amount of distortion. To show how we might find the answer to such a problem, let's take some typical figures. We'll assume that the signal voltage has a maximum peak-to-peak value of 6 volts, that we have a B supply of 240 volts, and that we plan to use a 6J5 triode. On the 6J5 plate family, we try pivoting the load line from the 240-volt point on the plate-voltage axis as in Fig. 23-11. To minimize distortion, we select our grid bias E_c so that a peak signal will not drive the grid positive. It is good practice to select the bias at least one volt more negative than the peak signal swing. We might select -5 or -6 volts. But as the bias is increased, the r_p of the tube is increased. This decreases the voltage gain, which is not desirable; for we are looking for as much gain as possible. So we use an E_c of -4 volts as our operating point on each of our trial load lines. We find that we get a greater voltage gain the nearer our load line comes to being parallel with the plate-voltage axis. There is a practical limit of course; for the more nearly parallel the load line becomes, the greater is the resistance of R_L , and the poorer the high frequency response of the amplifier becomes.

In a later lesson, we will discuss the resistance-coupled amplifier charts that appear in the back of your RCA Receiving Tube Manual. Further information must be given to you on biasing methods before these tables can be made useful to you.

23-7. TETRODE AND PENTODE VOLTAGE AMPLIFIERS

While most of the audio voltage amplifiers in radio and television receivers use triodes,

some such voltage amplifiers use tetrodes or pentodes. (Actually tetrodes are used so very seldom as voltage amplifiers that we will speak of pentodes mostly in the following.) The use of pentodes in voltage amplifiers is usually limited to applications where high voltage gain is necessary. A public address system usually has a stage or two of pentode voltage amplification following the microphone, where the input signal is very weak, and high gain is necessary. So some mention of pentode voltage amplifiers should be made here.

Where the required output signal is small, about 20 volts or less, pentodes usually have less distortion than triodes. For high power amplifiers, the voltage amplifier output may need to be as much as 100 volts peak-to-peak or more, and in this case, triodes produce less distortion.

As you know, the plate resistance of tetrodes and pentodes is high - - much higher than that of typical triodes. For example, the plate resistance of a 6SJ7 ranges normally between about 0.7 and 1.0 megohm. If we think of the output a-c plate voltage of the tube being divided between the plate resistance and the load resistance (as in the case of a triode), it looks like we need a load resistance of very high value. This is not practical, because all of the B voltage would be dropped across the load and little or no voltage would reach the plate. So, as a matter of practice, the load resistance of a pentode is usually only a fraction of the value of the plate resistance. This would make it appear that we get very poor gain from a pentode, which is not the case. A little figuring will show why.

The μ of the 6SJ7 (operating as a pentode) is not given in the tube manual, and that's because the actual gain, under any particular set of operating conditions, depends upon more than just the proper selection of a plate load. However, we can get a rough estimate of the μ of the tube by using the formula:

$$\mu = r_p g_m$$

The tube manual shows a plate resistance of 700,000 ohms for the 6SJ7 (operating with 100 volts on the plate and screen) and a transconductance (g_m) of 1,575 μ mhos. Remembering that 1,575 μ mhos = 0.001575 mhos, we find the amplification factor:

$$\begin{aligned}\mu &= 700,000 \times 0.001575 \\ &= 1,100 \text{ (approx)}\end{aligned}$$

From this, you can see that, with such a high amplification factor, even a small value of R_L would produce a high voltage gain when compared with a triode.

The voltage gain of an amplifier circuit, you recall, is:

$$\text{Gain} = \mu \frac{R_L}{R_L + r_p}$$

We know that $\mu = r_p \times G_m$, so we substitute μ in the formula:

$$\text{Gain} = r_p G_m \frac{R_L}{R_L + r_p}$$

Rearranged, it becomes:

$$\text{Gain} = G_m \frac{R_L r_p}{R_L + r_p}$$

However, for pentode tubes, R_L is small with respect to r_p , so the voltage gain of a pentode amplifier stage becomes:

$$\text{Gain} = G_m \frac{R_L r_p}{r_p} = G_m R_L$$

Pentode Curves. The operating conditions for a pentode (or tetrode) may be determined in the same ways as for a triode. Because you have more use for such information when studying power amplification, full instructions for drawing load lines on pentodes are given in the lesson on Power Amplifiers.

APPENDIX A – ELECTRON-TUBE LETTER SYMBOLS

The letter symbols below, which are used to represent the different voltages and currents involved in electron tubes and electron tube circuits, are in agreement with those given by the Institute of Radio Engineers and are used by most standard textbooks.

Each symbol consists of a letter and a subscript. The letter identifies a voltage or current, and the subscript identifies an electrode of the tube concerned. The letters E and e are used to represent voltages, while the letters I and i are used to represent currents. Capital letters are used to stand for either *steady* voltages or currents, or the *rms* value of a-c voltages and currents. Lower case letters stand for *instantaneous* values of a varying signal voltage or current.

All subscripts are lower case. Only a few subscripts are used: b, p, c, and g. The subscripts b and p both mean that the voltage or current applies to the plate circuit. The b subscript is used to represent the *total* value (d.c. plus a.c.) from plate to cathode; the p subscript is used to represent the value of a.c. or signal component between plate and cathode. The remaining subscripts c and g both apply to the grid circuit; the c subscript is applied to the *total* value (d.c. plus a.c.) between the grid and cathode of a tube, while the g subscript is applied to the value of the a.c. or signal component between grid and cathode. The use of the subscripts b and c for plate and grid stems from the early days of radio, when the plate supply battery was called the "B" battery, and the grid supply battery was called the "C" battery. The a-c subscripts p and g are

the first letters of the words plate and grid, respectively.

Double subscripts are used to indicate sources, such as the B voltage supply, which is designated E_{bb} , and they are used only with capital letters.

Examples of the use of these symbols are given in the following tabulation and shown in the figure below.

e_b, i_b, e_c = instantaneous total value of voltage (or current) from plate (or grid) to cathode.

e_p, i_p, e_g = instantaneous value of *signal component* of plate (or grid) voltage (or current)

E_b, I_b, E_c = d-c voltage (or current) from plate (or grid) to cathode with no input signal

E_p, I_p, E_g = effective (rms) value of the *signal component* of the plate (or grid) voltage (or current)

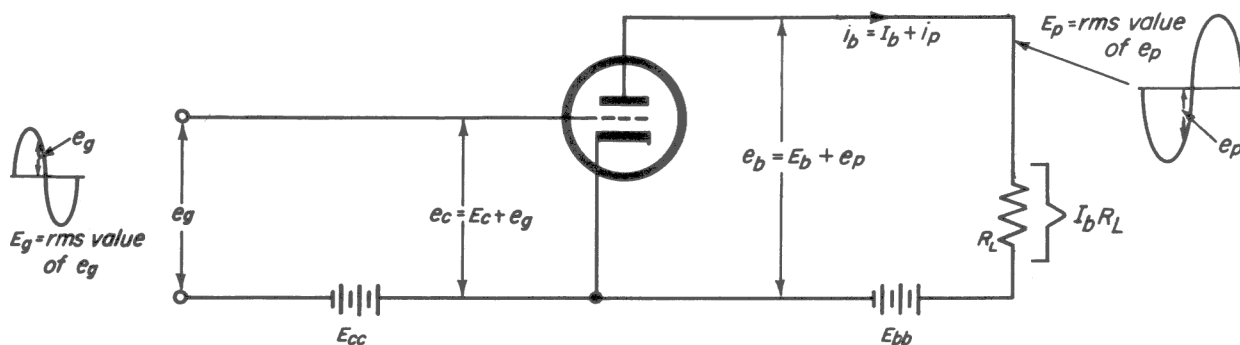
The relationship between the various symbols can also be further illustrated by the following equations:

$$e_b = E_b + e_p$$

$$i_b = I_b + i_p$$

$$e_c = E_c + e_g$$

$$E_b = E_{bb} - I_b R_L$$



APPENDIX B - HARMONIC DISTORTION

In almost all cases, the output signal from an amplifier circuit is not an exact amplified likeness of the input signal, but is more or less different from the input signal. A typical example is shown in Fig. 1. The output wave is said to be *distorted*. The distortion occurs because the combination of input signal amplitude, load resistance, and operating voltages is such that the non-linear portion of the tube characteristic curve is used.

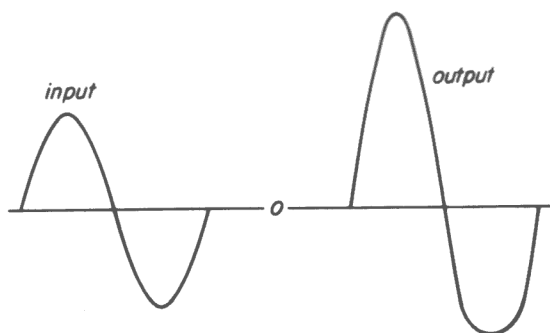


Fig. 1

The distorted waveform shown is composed of a certain amount of d.c. plus an infinite number of *harmonics*. Harmonics are pure sine waves whose frequencies are multiples of the frequency of the input signal frequency. The first harmonic, or *fundamental*, is the signal. The second harmonic is a sine wave whose frequency is twice that of the original signal, the third harmonic is a sine wave whose frequency is three times the original signal, and so on. Any distorted waveform of the type shown in the figure can be resolved (separated) into a certain amount of fundamental, plus a certain amount of second harmonic, plus a certain amount of third harmonic, and so on. Although the harmonics result from the non-linearity of the tube, each harmonic is a pure undistorted sine wave. The distortion is due to the combination with the fundamental of the second and higher harmonics.

As the frequencies of the harmonic components in a wave increase, their amplitudes decrease. The second harmonic component

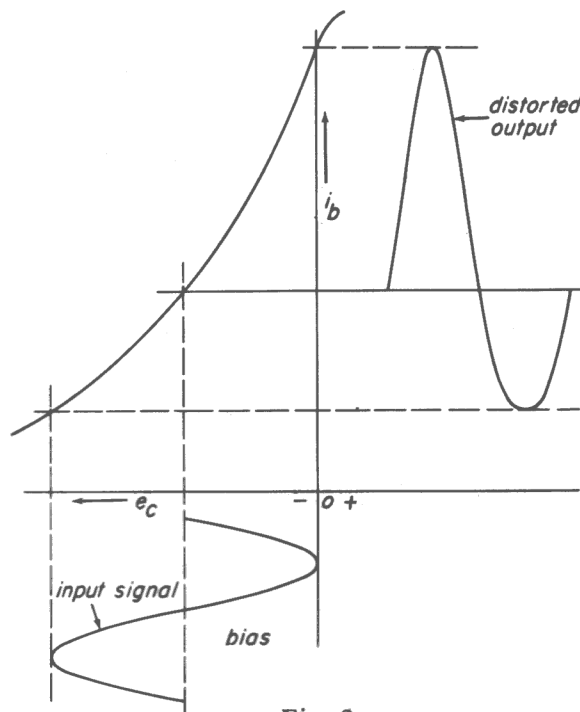


Fig. 2

has the largest amplitude and the higher harmonics become successively smaller until they are too small to be considered. Usually, only the second and third harmonic components need be considered.

Let's consider an example of how a sine wave can become distorted due to non-linear amplifier operation, and how this non-linearity can be represented by harmonics.

In Figure 2, a sine-wave input signal is shown applied to a tube operating curve.

Here, because of the operating bias used, the signal is applied to the non-linear part of the tube's characteristic curve. Because of the large input signal amplitude, the lower portion of the output current wave is compressed as shown. This type of amplitude distortion is typical. Figure 3 shows how a similar distorted wave can be obtained by a combination of pure sine-wave harmonics. A distorted output such as the wave of Fig. 2 can be obtained by adding a certain amount of d.c., plus a certain amount of

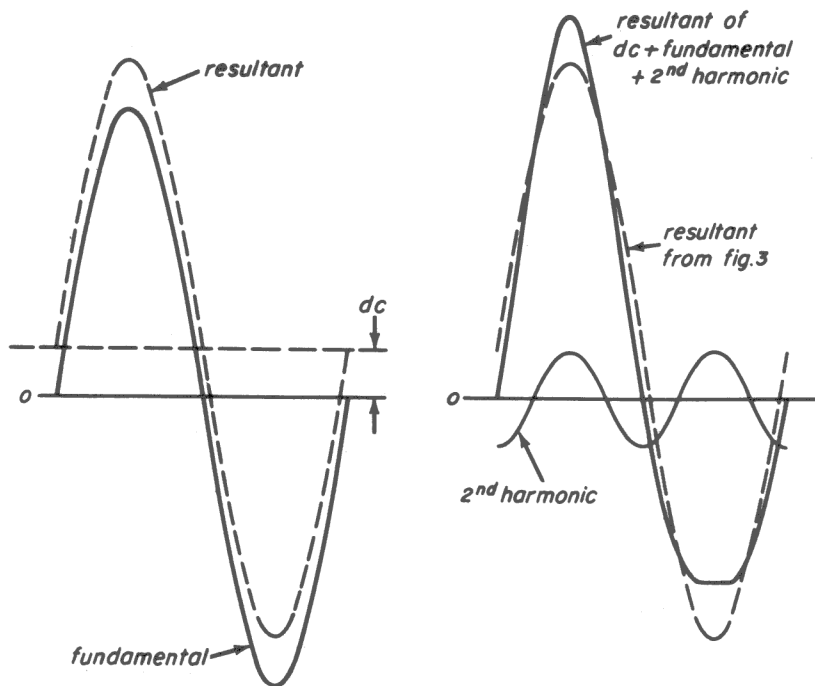


Fig. 3

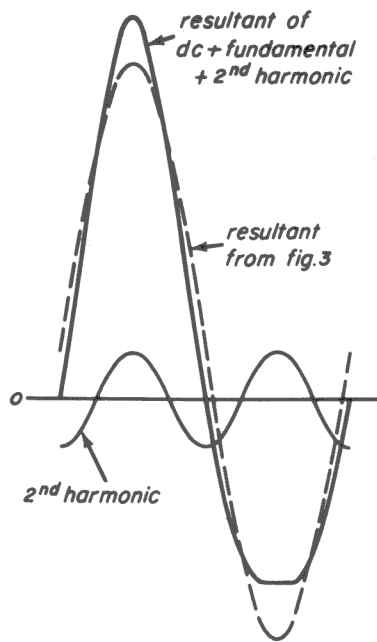


Fig. 4

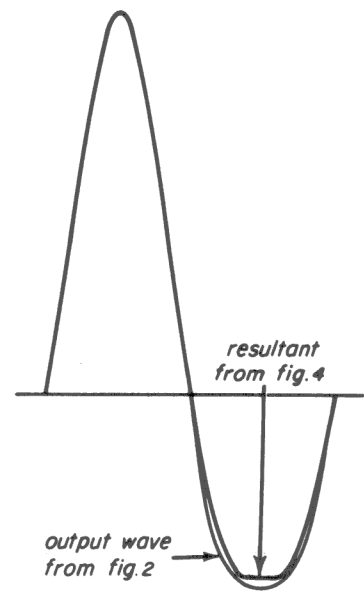


Fig. 5

fundamental, plus a certain amount of second harmonic, plus a certain amount of third harmonic, etc. Because the third and higher harmonics are small, the addition of only the fundamental and second harmonic as shown in Fig. 4 without any other harmonics gives a very close approximation to the actual output wave shown in Fig. 2.

A certain amount of d.c. is needed because the output wave is no longer symmetrical. It is more above the baseline than below it. The addition of the d.c. and the fundamental is shown in Fig. 3. To this resultant, the second harmonic is added in Fig. 4. Figure 5 compares this resultant with the actual distorted output wave, and the closeness of the two can be readily seen. As higher harmonics are added, the resultant will become more and more like the actual output wave.

The percentage of harmonic distortion is defined below:

$$\text{percentage of harmonic distortion} = \frac{\text{amplitude of harmonic}}{\text{amplitude of fundamental}} \times 100$$

The percentage of distortion must be found separately for each harmonic, for as many harmonics as have important components. The total harmonic distortion can be expressed as follows:

$$\text{total harmonic distortion} = \frac{\text{the square root of the sum of the squares of each of the harmonics}}{\text{amplitude of fundamental}}$$

In certain types of distortion, only the even harmonics are present; while others contain only the odd harmonics. Other types of distorted waves may contain both the even and the odd harmonics.